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Persisting and strong warming hiatus over eastern China during the past two decades

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Abstract

During the past two decades since 1997, eastern China has experienced a warming hiatus punctuated by significant cooling in daily-minimum temperature (Tmin), particularly during early–mid winter. By arbitrarily configuring start and end years, a 'vantage hiatus period' in eastern China is detected over 1998–2013, during when the domain-averaged Tmin exhibited the strongest cooling trend and the number of significant cooling stations peaked. Regions most susceptible to the warming hiatus are located in North China, the Yangtze–Huai River Valley and South China, where significant cooling in Tmin persisted through 2016. This sustained hiatus gave rise to increasingly frequent and severe cold extremes there. Concerning its prolonged persistency and great cooling rate, the recent warming hiatus over eastern China deviates much from most historical short-term trends during the past five decades, and thus could be viewed as an outlier against the prevalent warming context.

1. Introduction

A large body of literature has reported a much smaller warming rate in the global mean surface temperature during 1998–2012 than over the past 30–60 years, a phenomenon termed the 'global warming slowdown' or 'hiatus' (Kosaka and Xie 2013, IPCC AR5 2013). The obvious mismatch between model-expected accelerated warming and observed flattening trend during 1998–2012 has motivated considerable explorations in its cause, mainly from perspectives of changes in radiative forcing, ocean heat uptake and internal variability modes (England *et al* 2014, Santer *et al* 2014, Drijfhout *et al* 2014). Regardless of these plausible mechanisms, some studies negated the existence of warming hiatus, after accounting for uncertainties in trend estimates caused by inadequate data coverage, diverging selections of start/end years, and the lack of statistical significance (Karl *et al* 2015, Lewandowsky *et al* 2015, Rajaratnam *et al* 2015). Obvious divergence of existing views concerning the warming hiatus actually accentuates the necessity of assessing regional contributions/responses (Trenberth 2015) and developing/employing a proper method to pin down an exact hiatus period (Lewandowsky *et al* 2015).

Detailed insights identified pronounced non-uniformities in both spatial and seasonal distribution of the warming hiatus (Trenberth *et al* 2014, Cohen *et al* 2012). The warming slowdown seemed largely dedicated by wintertime temperature changes at mid-latitudes over Eurasia and North America (Karl *et al* 2015, Gleisner *et al* 2015, Li *et al* 2015a). Apart from assessing regional contributions, impacts of the warming hiatus on regional temperatures were also examined (Vuille *et al* 2015, Li *et al* 2015b, Gonzalez-Hidalgo *et al* 2015), yet leaving resulting behaviors of temperature extremes strikingly under-studied (Sillmann *et al* 2014, Fonseca *et al* 2016). During the past two decades, East Asia and North America experienced several harsh winters punctuated by usually intense cold air outbreaks (Kug *et al* 2015, Sun *et al* 2017). Causal relationships between the increasing presence of cold extremes and the warming hiatus are desirable to be further disentangled.

The choice of start year could substantially influence the sign, magnitude and significance of estimated trends, and thus determines the identifiability of warming hiatus. This key parameter, however, varied greatly through the literature, spanning from the early 1990s to the early 2000s (Lewandowsky *et al* 2015). Considering a strong El Niño event in 2015 and a resumption of a positive PDO (Pacific Decadal Oscillation) phase, some studies announced an termination of the hiatus in 2013 (Trenberth 2015, Hu and Fedorov 2017). By contrast, other studies indicated that the hiatus has persisted through 2015, and would possibly stay alive for another few years (Robert *et al* 2015, Schurer *et al* 2015, Knutson *et al* 2016). The usage of increasingly available observations after 2013 could gain confidence in answering whether and when the hiatus has come to an end, at both regional and global scales.

China is coincidentally located within an intersected region between the latitudes and longitudes most susceptive to the warming hiatus (Li *et al* 2015a). By prescribing the period over 1998–2012/2013, several studies have confirmed the existence of hiatus in China (e.g. Li *et al* 2015b, Xie *et al* 2017). However, *a priori* justification for applying the 'global warming hiatus period' to regional scales is warranted yet scarcely implemented. Consequently, whether and where the warming hiatus in China is still proceeding or has terminated remains an open question. In the context of warming hiatus, changes in temperature extremes, particularly cold extremes in China, have hitherto been rarely reported. Additionally, the extent to which the recent warming hiatus deviates from its historical counterparts deserves assessing through comprehensive comparisons. This study attempts to narrow above-mentioned gaps via unraveling regional peculiarities of the warming hiatus in China.

2. Data and method

2.1. Data preparations

Both at the global scale and in China, winter (December–January–February) recorded the most obvious warming hiatus (Li *et al* 2015b, Medhaug *et al* 2017). So this study focuses on temperature changes in winter. Daily mean, maximum and minimum temperatures (Tmean/Tmax/Tmin) during 1961–2016 are collected from a dataset of 756 stations, provided by the National Meteorological Information Center (NMIC). Having been subject to rigorous quality controls, this dataset is recognized as an excellent tool for climate research (Zhai *et al* 2005). To minimize potential influences of missing values and inhomogeneity on trend estimates, additional pre-processing is required as follows:

1. Missing data accounts for less than 5% in wintertime records each year;
2. Throughout 1961–2016, site displacement should be within 20 km horizontally and 50 m vertically.

Satisfying the above criteria, a total of 379 stations are retained.

2.2. Method

For winter-mean Tmean, Tmax and Tmin, their linear trends are calculated via ordinary least squares slope estimator, along with significance level estimated by a two-tailed Student's *t*-test. For intensity and frequency of temperature extremes, their linear trends and significance level are quantified by the Kendall's tau method, the proper and widely-used one for examining extremes (Sen 1968).

A warm/cold extreme is defined as an event with its Tmean/Tmax/Tmin exceeding the 90th/10th percentile of its long-term (1971–2000) counterparts. For each calendar day, its 90th/10th percentile of temperature variable is derived from multi-year sample units of 15 days (seven days on either side of this specific day) over the baseline period (i.e. total samples $15 \times 30 = 450$ days, Della-Marta *et al* 2007). The intensity of warm/cold extremes is represented as the departure of temperature variables above/below their thresholds. Altering the baseline period (e.g. 1961–1990; 1981–2010) did not influence trend estimates in any significant manner.

The probability density function (PDF) is computed with the kernel density estimation scheme (Worton 1989), which is free from any assumption of distributional forms of the original data.

3. Results

Previous studies have reported marked spatial heterogeneity of linear trends during the prescribed hiatus period (1998–2012/13), with cooling trends detected across widespread regions over eastern China and continued warming over western parts (Li *et al* 2015b, Duan and Xiao 2015, You *et al* 2015). Built on these achieved conclusions, the following analyses would concentrate on eastern China (east of 105°E, a total of 295 stations), and the hiatus there refers exclusively to a cooling trend, rather than the muted warming rate pertaining to the global scale.

The onset of hiatus was usually set at 1998, a strong El Niño year with high temperature considerably above its long-term counterparts (IPCC AR5 2013). However, moving back or forward the start point by just one or two years may lead to a rate close to the long-term trend, thus a denial of the hiatus (Lewandowsky *et al* 2015). Tmean is the variable commonly used to delineate the hiatus, but changes in mean temperature may represent a compromise of disproportionate changes in Tmax and Tmin (IPCC AR5 2013, Gonzalez-Hidalgo *et al* 2015). Individual behaviors of Tmax and Tmin are therefore worth further inspecting to quantify their contributions and responses to the hiatus. Accordingly, we estimated respective trends for Tmax and Tmin, by arbitrarily configuring any start year among 1996–2000 and any end year among 2011–2016. As indicated by figures 1(*a*)–(*b*), Tmin exhibited more sensitive responses, evidenced by significant cooling trends over much broader areal extent, around a tripling

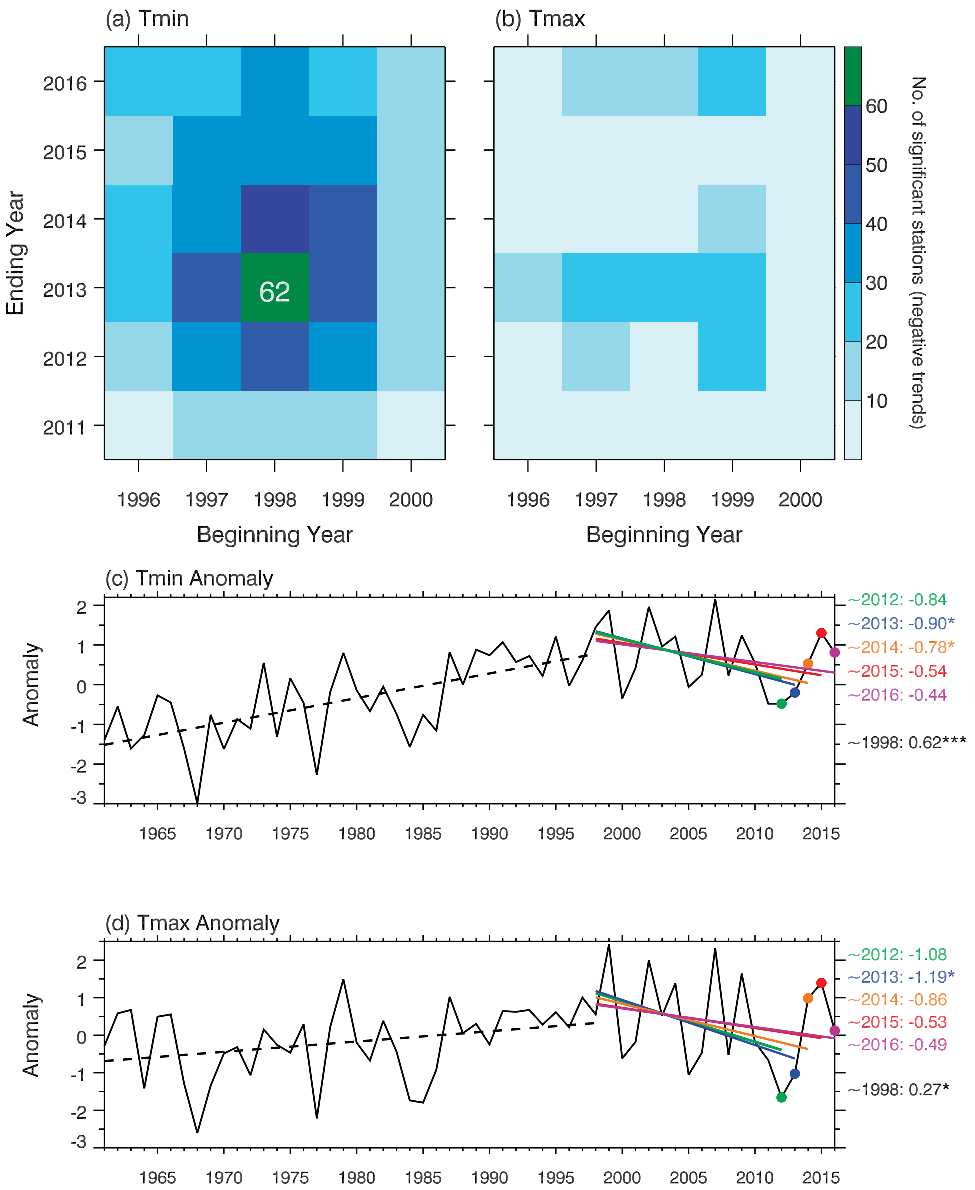

Figure 1. The number of stations in eastern China that observed significant cooling in Tmin (*a*) and Tmax (*b*) during intervals with different start years (*x*-axis) and end years (*y*-axis). The white number in (a) labels the maximum number of significant cooling stations, (*c*) and (*d*) show domain-averaged (east of 105 °E) Tmin and Tmax anomalies (solid black curves), respectively. In (*c*) and (*d*), colored curves show linearly-fitted results with their beginning year in 1998 and ending year ranging from 2012 to 2016 as specified by corresponding colored dots; while dashed black curves indicate linearly-fitted anomalies during 1961–1998. Respective linear trends (°C decade^{-1}) ending at differing years are also listed in corresponding colors, with '*', '**', and '***' indicating their significance at the 0.1, 0.05 and 0.01 level.

of that for Tmax. Though start/end years of the hiatus differ among stations, the most significant hiatus period ('vantage hiatus') over eastern China is preferably defined as the interval over 1998–2013, during which more than 20% of stations recorded significant cooling trends for Tmin. Given a significance at the 0.1 level, the vantage hiatus still began at 1998 but ended at 2014 instead (figure omitted), with the percentage of significant cooling stations (91) reaching 31%. So the El Niño year in 1998 seems proper to be set as the beginning of the vantage hiatus in eastern China. Without constraints on statistical significance, the number of cooling stations peaked during 1998–2013 as well, with the percentage climbing up to 96% (284). However, the magnitude and sign of trends during a period shorter than 20 years may be highly variable due to the inclusion of 1–2 extremely warm/cold years. Hence, adequate significance is imperative to differentiate robust signals of climate change from random noisy variability (Lewandowsky *et al* 2015). As such, the proposed concept of vantage hiatus serves to portray the regional-scale hiatus by emphasizing a significant cooling period collectively registered by most extensive areas, but it may be just an episode of the entire cooling regime (significant or insignificant) at individual station level. As for domain-averaged series (figures 1(*c*)–(*d*)), the vantage hiatus period over 1998–2013 is characterized by the largest magnitude

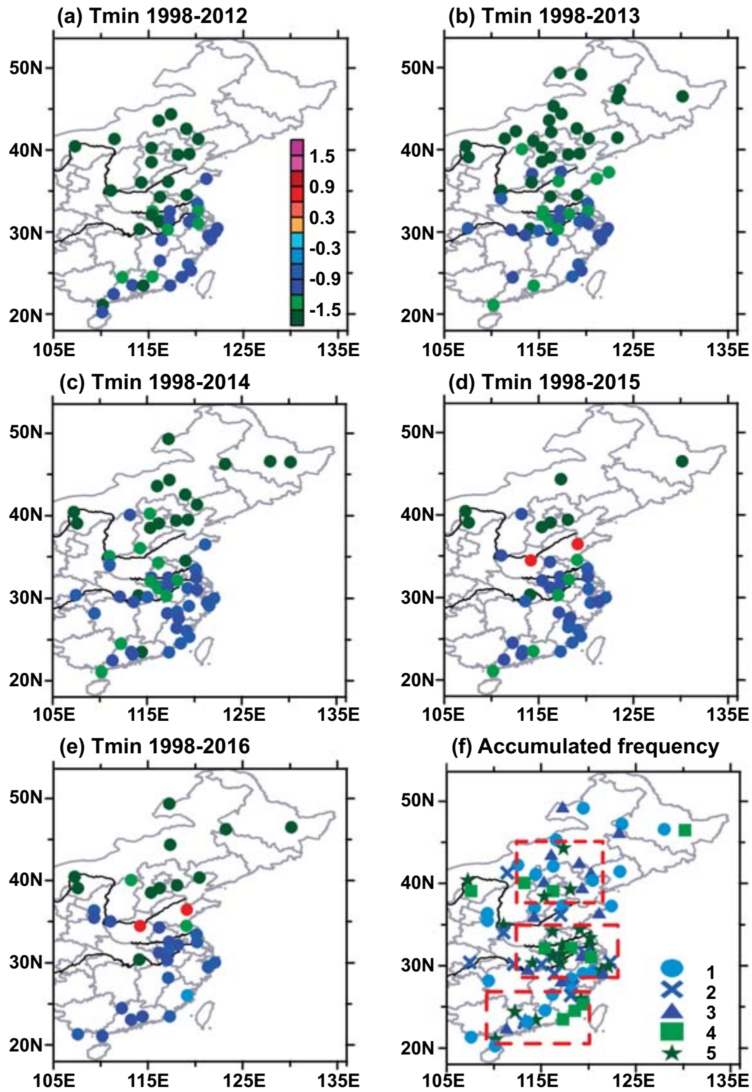

Figure 2. Linear trends (°C decade^{-1}) for Tmin (*a*)–(*e*), with the start year set at 1998 and end year varying among 2012–2016. (*f*) Accumulated occurrences of significant cooling trends ending at differing years among 2012–2016. For instance, the accumulated frequency of 5 (stars) means a significant cooling trend was detected over all intervals of 1998–2012, 1998–2013, 1998–2014, 1998–2015, and 1998–2016. In (*a*)−(*e*), only trends significant at the 0.05 level are shown. Three rectangles in (*f*) locate regions that experienced persisting significant cooling, as indicated by green squares and stars.

of cooling trends. Though the cooling in Tmax seems slightly stronger, trends for Tmin are of higher significance (*p*-value of 0.06 for both 1998–2013 and 1998–2014 in Tmin, and *p*-value of 0.09 for 1998–2013 in Tmax). Moreover, sharper contrast between trends before and after 1998 renders Tmin more appropriate to characterize the reversal from rapid warming into subsequent hiatus (Rajaratnam *et al* 2015). So in the following section, Tmin is adopted to measure the warming hiatus in eastern China.

Figure 1 remains unable to locate regions most susceptible to the warming hiatus. With the start year fixed at 1998, significant cooling trends for Tmin persisted through 2016 in a few sub-regions, particularly in the Yangtze–Huai River Valley, parts of North China and South China (red rectangles in figure 2(*e*)). Replacing the start year with 1997 or 1999, regions that registered persisting (~2016) cooling trends remain basically unchanged (see supplementary figure S1, available at stacks.iop.org/ERL/12/104010/mmedia). So, over these regions, inclusion of recent warm years (2014–2016) failed to terminate the significant hiatus. Apparently, these key regions are the very source that the domain-averaged series' persisting cooling tendency since 1998 originates (figure 1(*c*), also see Li *et al* 2017). For most stations, the strongest cooling trend occurred within the period over 1998/1999–2012/2013 (figure S2). In other words, although the significant hiatus is still advancing, its magnitude has been somewhat abated by reappearance of warm years during 2014–2016. This phenomenon could also be validated by gradually reduced cooling rates after 2013 in the domain-averaged series, as labeled in figures 1 (*c*)−(*d*).

Climate change and its consequences are often perceived through climate extremes occurring at regional scales (Seneviratne *et al* 2012). Commensurate with the persisting cooling, more occurrences of cold

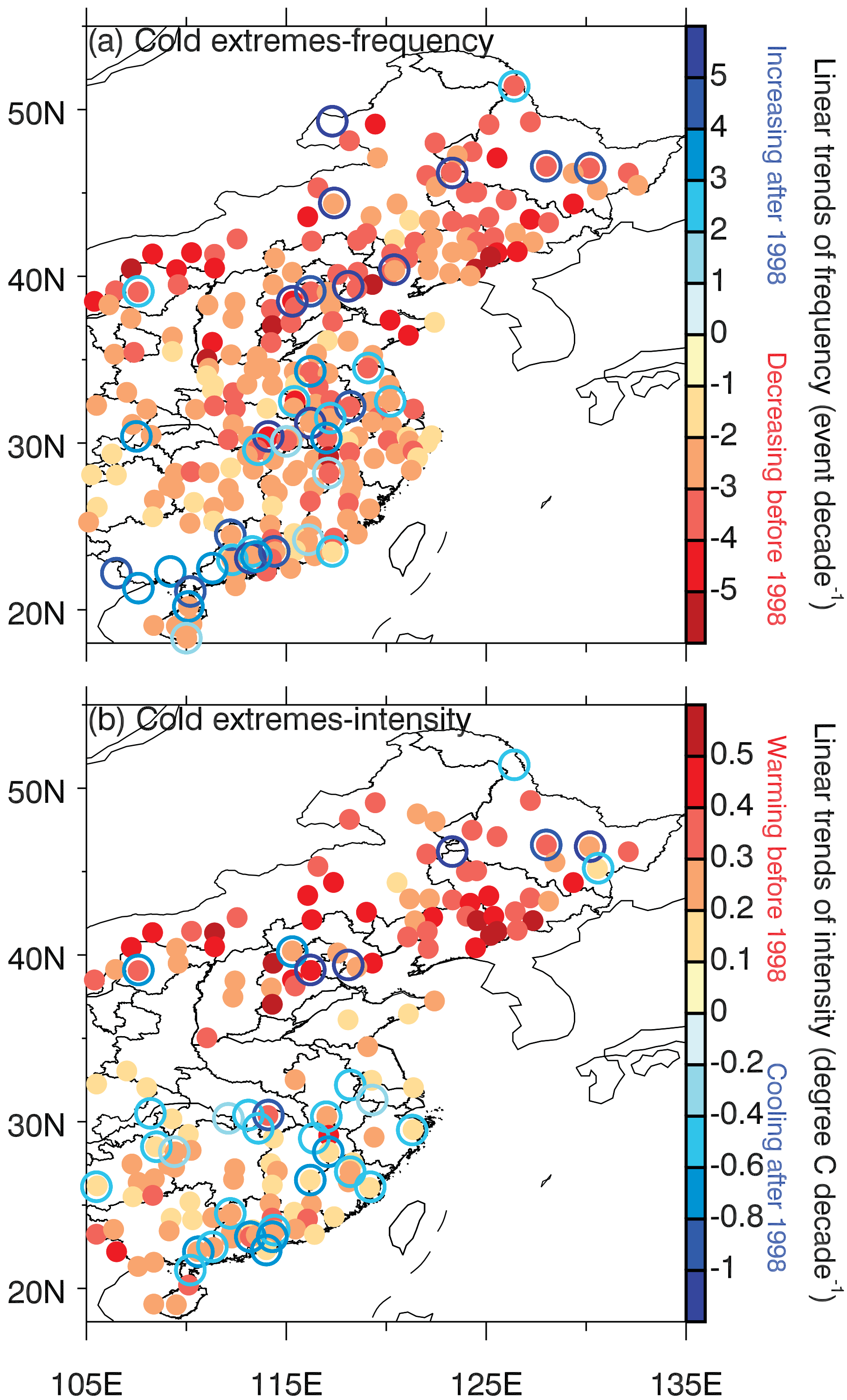

Figure 3. Linear trends for frequency (*a*) and intensity (*b*) of cold extremes. In (*a*), red dots indicate significantly decreasing trends for frequency during 1961–1998; while blue circles show the strongest increasing trend among significant ones with the start year in 1998 and end year varying among 2012–2016. In (*b*), red dots show significantly warming trends for intensity during 1961–1998; while blue circles show the strongest cooling trend among significant ones with start year in 1998 and end year varying among 2012–2016.

extremes were observed over above susceptible regions since 1998, with significantly enhanced intensity. Thus, opposing trends for cold extremes before and after 1998 further underpin the existence of observed hiatus (figure 3). A question of whether increasing occurrences of stronger cold extremes produced the hiatus in eastern China would be raised naturally (Sillmann *et al* 2014, Fonseca *et al* 2016). After eliminating all cold extremes in each winter, the vantage hiatus period is still anchored over 1998–2013 (figure 4(*a*)). Further, with these cold extremes included or not, spatial patterns for the hiatus did not change in a striking manner (compare figure 4(*c*) and figure 2(*f*)). So the persisting cooling actually acted as a favorable

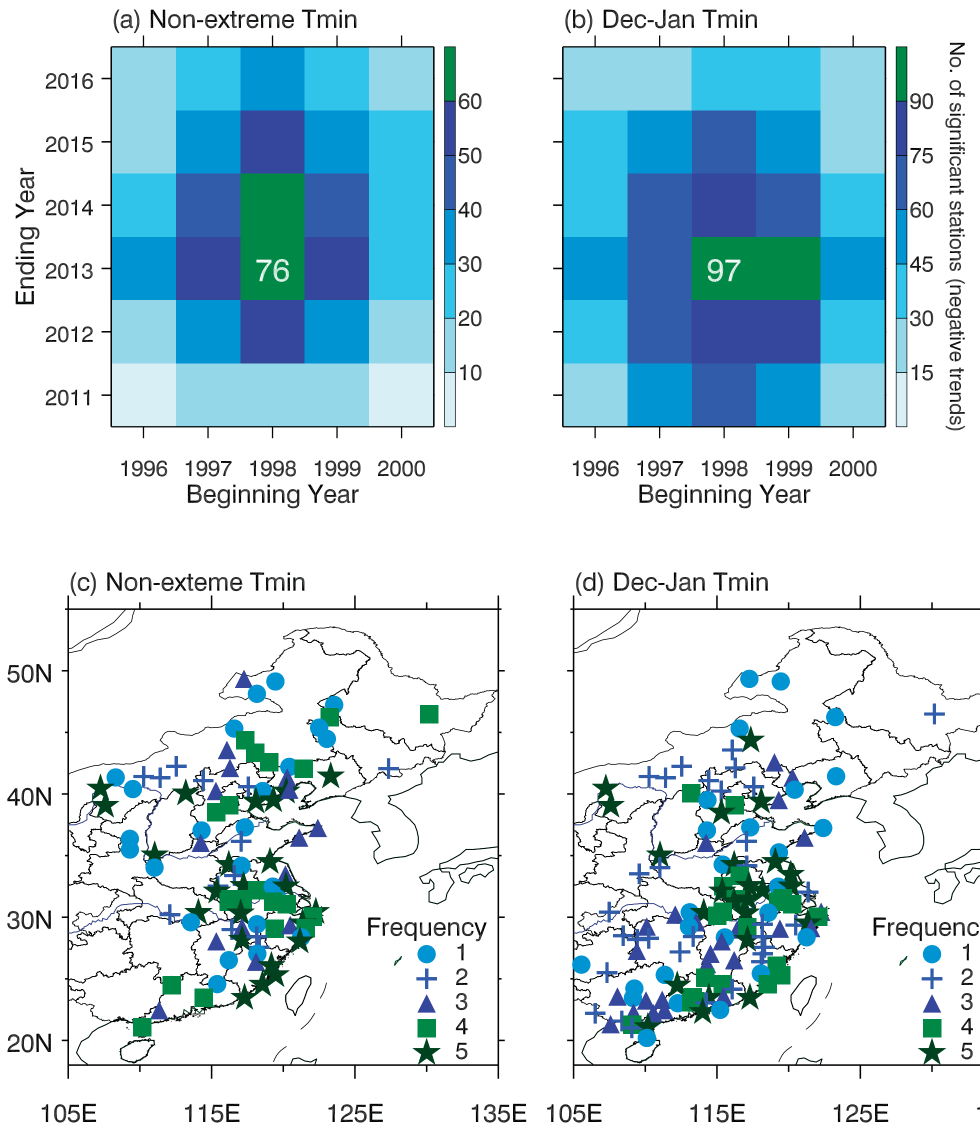

Figure 4. (*a*) and (*b*), same as figure 1(*a*) but for Tmin averaged among non-extreme days (*a*) and December–January days (*b*). (*c*) and (*d*), same as figure 2(*f*), but for Tmin averaged among non-extreme days (*c*) and December–January days (*d*).

backdrop that brought on increasing occurrences of stronger cold extremes, rather than a passive consequence induced by the recent boom of cold extremes. Accordingly, the ongoing warming hiatus may at least partially explain some severe cold extremes in a warmer climate after 2000 (such as the record-breaking low daily-Tmin in above regions in January 2016, as shown in figure S3). Scrutiny of intraseasonal (monthly) Tmin during winter found the vantage hiatus period and trend maps for Tmin in December and January were highly similar, also consistent with the winter-mean situation. However, significant cooling trends for February Tmin failed to be detected in most stations (over 97%), regardless of start/end points configured. So the significant hiatus was primarily contributed by changes in December–January Tmin, as illustrated by figures 4(*b*) and (*d*). Of particular note is that during early–mid winter, almost all of southern China has experienced a significant hiatus, despite differing persistency among stations. Notably, during the vantage hiatus period for early–mid winter, around 33% stations (97) observed significant cooling simultaneously (figure 4(*b*)).

Placing the recent hiatus into historical context, it could be found that significant warming in Tmin is undisputed if setting the beginning point no later than 1986 (figure 5(*a*)). After that, during the interval beginning from either year within 1987–1996 and ending before 2010, the warming tendency continued with a diminishing magnitude and significance. Extending the end year to 2011–2016, cooling trends began to emerge. So this period (1987–1996) is a 'transient interval', which prolonged pre-existing warming and initiated longer-term cooling. From 1997 onward, cooling trends became prevalent, irrespective of selected start point and interval length. These pan-cooling trends indicate that the regional hiatus/cooling actually got started since 1997. Moreover, the cooling trend for the interval containing years after 2011 showed higher significance and larger magnitude.

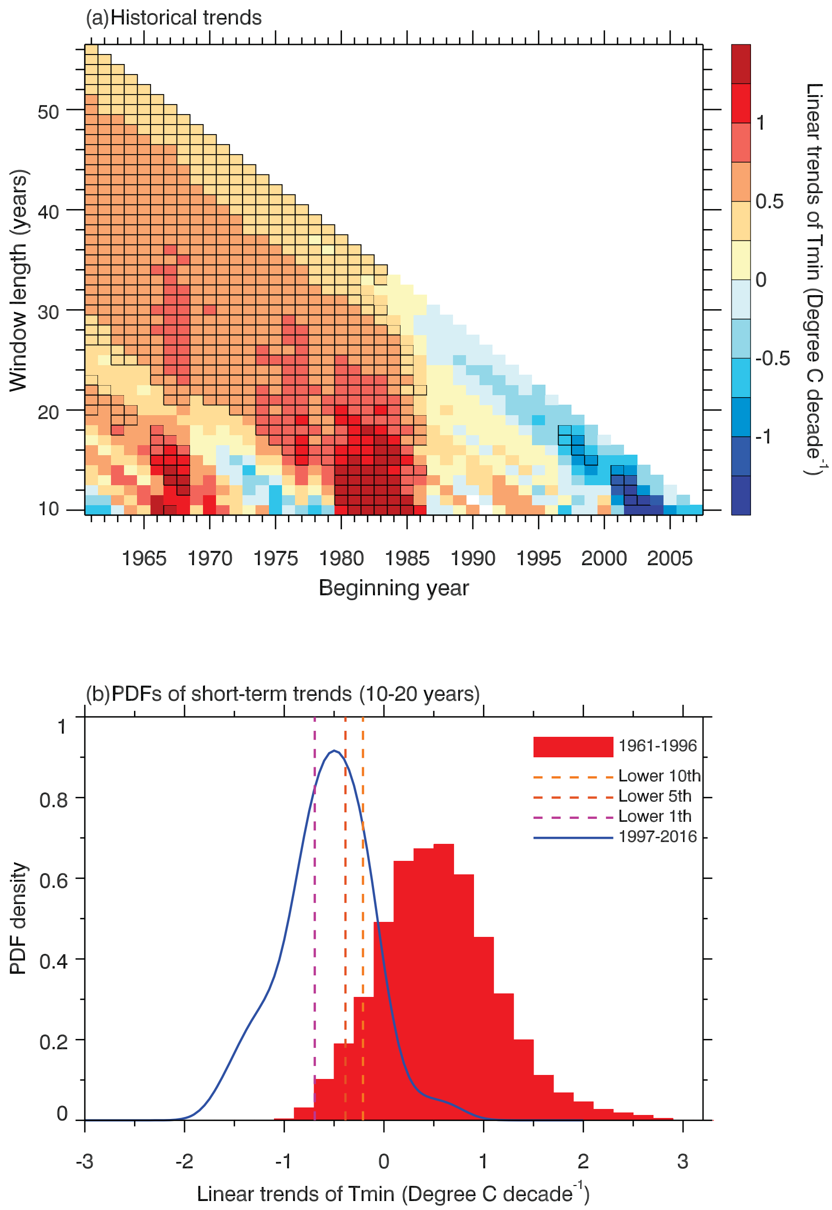

Figure 5. (*a*) Historical trends (°C decade^{-1}) for domain-averaged Tmin with differing start years and interval lengths. All trends significant at the 0.1 level at least are enclosed by black squares. (*b*) PDFs of all short-term (10–20 years) trends, which began before 1996 (red histograms) and after 1997 (blue curves). Three vertical dashed lines locate the lower 10th, 5th and 1st percentile of all short-term trends during earlier period (starting before 1996).

Regarding its lifespan, recent coherent cooling is unprecedented under the background of predominant warming. The PDF of short-term (10–20 years) trends was further used to illustrate such abnormality of the recent hiatus. The historical PDF curve and the recent one diverges significantly, with the former positively skewed (warming) and later negatively skewed (cooling). A percentage of 82%, 65% and 38% for short-term trends during the recent hiatus fall beyond the lower 10th, 5th and 1st percentile of historical counterparts, respectively (figure 5(*b*)). Around 34% trends during the recent hiatus are of larger cooling rate than any observed short-term trend before 1997. Thus, it is reasonable to define the recent hiatus as an unusual or even an extreme scenario against the background warming, characterized by its strong magnitude and long persistency of the cooling tendency.

4. Conclusions and discussions

4.1. Discussions

When interpreting the recent hiatus, the start point or the reference point (around 1997–1999) should be explicitly specified. The occurrence of recent hiatus cannot be used as an excuse to rebut or even deny the fact of long-term climate warming at both global and regional scales (Medhaug *et al* 2017). As indicated in figure 5(*a*), any interval longer than 30 years recorded a significantly positive trend, reinforcing the unequivocal fact of long-term warming. In particular, this long-term warming has cultivated a much warmer regime after 1990 (figures 1(*c*) and (*d*)), with nearly every year seeing warm winter and all record-breaking warmth occurring during this period. The majority of cooling trends over eastern China are typical of short-term (less than 20 years) internal variability, consistent with previous findings (Meehl and Teng 2014, Fyfe *et al* 2016). Albeit continued hiatus in some vulnerable regions, steady increase of greenhouse gas emission and a gradual reversal of PDO phase leave little room for reoccurrence of a similar hiatus in the future (Knutson *et al* 2016, Roberts *et al* 2015, Maher *et al* 2014).

Until now, proposed candidate mechanisms were mainly documented from thermodynamic (both natural and anthropogenic) perspectives (Maher *et al* 2014). What's more, these thermodynamic mechanisms were more inclined to be leveraged to explain the global-scale warming hiatus (e.g. Watanabe *et al* 2014, Huber and Knutti 2014). Inferred from relevant studies for the hiatus over the Eurasian continent and China, the persisting cooling trend over eastern China may possibly be ascribed to increasing local aerosol loading (Smith *et al* 2016), rising heat uptake by the nearby ocean (like the North Pacific, Chen and Tung 2014), rapid Arctic sea ice decline (Mori *et al* 2014), or a transient regime of low-level solar radiation (Du *et al* 2017). Enough cautions, however, should be warranted about the role of solar irradiance changes in triggering the warming hiatus, considering large uncertainties among differing datasets of solar activity (Soon *et al* 2015). At a regional scale, dynamic effects, i.e. changes in circulation patterns, in generating the warming hiatus are believed to be critical yet remain less addressed (Li *et al* 2015a). By employing 'circulation analogue' method (Yiou *et al* 2007, for details see supplement #4), it could be found that dynamic effects were fully responsible for occurrences of cold winters after 1998, which might have behaved even harsher (the lower boundary) if only accounting for dynamic influences (figure S4, see the lower boundary of the envelope). Starting in late 1980s, any subsequent intervals of 10–30 years observed cooling trends in dynamically-induced component, contributing much to the cooling trends during the 'transient interval' as mentioned above (figure 5(*a*)). This dynamically-induced cooling may be closely associated with the recovery of the Siberian high and East Asian winter monsoon (Jeong *et al* 2011, Wang and Chen 2014). While, during warm winters after 1990, superimposing on dynamically-induced mild warmth, the thermodynamic effects considerably amplified the warm anomaly. Among these thermodynamic contributions, the urbanization-caused warming rate should be particularly noted, since most urban stations are coincidently distributed over susceptible regions identified in figure 2(*f*) (Soon *et al* 2015). Measured by the magnitude of cooling trends for Tmin after 1998, the contribution from dynamic effects to the significant hiatus reached 23%–31%, depending on selected end points among 2011–2016. That is to say, the pre-existing dynamically-induced cooling (since 1987) was substantially exaggerated by the following enhanced contrast between the thermodynamic warmth and dynamically-induced coldness after 1998. That explains the dramatic growth in both magnitude and significance of cooling trends after 1998, as addressed by figure 5(*a*).

As revealed in above analyses, there is no evidence (figures 2, 4 and 5) indicating a termination of the recent warming hiatus in eastern China. The question of when the accelerated warming trend will resume needs to be answered by climate model prediction, which requires further validation via forthcoming observational data after 2016, in combination with the method developed in this study.

4.2. Concluding remarks

During the past one to two decades, eastern China has experienced a pronounced warming hiatus, manifested most obviously by significant cooling in mid–early winter (December–January) minimum temperature. Through arbitrarily configuring start and end years, a 'vantage hiatus period' is identified over 1998–2013, characteristic of the maximum number of significant cooling stations (more than 20%) and strongest cooling trend for domain-averaged Tmin. Anchoring the start year around 1998 (1997–1999), significant cooling persisted through 2016 over North China, the Yangtze–Huai River Valley and South China. This sustained cooling facilitated increasing occurrences of cold extremes of greater intensity in above regions. In terms of cooling magnitude and duration, the recent hiatus in eastern China may be viewed as an abnormal event of reasonably low occurrence probability (lower than 10%). Such a rare hiatus arose mainly from a sharpened contrast between thermodynamically-induced warmth and dynamically-induced coldness after 1998.

Acknowledgments

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